PAPER REF: 3862

ANALYSES OF STIFFNESS DEGRADATION EFFECTS DUE TO LOW CYCLE FATIGUE DAMAGE IN METALLIC STRUCTURES

Mohammad Saranik [1(*)], Louis Jézéquel [1], David Lenoir[1]

[1]Laboratoire de Tribologie et Dynamique des Systèmes, Département de Mécanique des Solides, Génie Mécanique et Génie Civil, Ecole Centrale de Lyon, 36 Avenue Guy de Collongue, 69134 Écully Cedex, France
[(*)]*Email*: mohammad.saranik@ec-lyon.fr

ABSTRACT

An approach for seismic analysis of a multi-degree-of-freedom system is proposed in this paper. The proposed approach can evaluate the seismic performance of steel portal frames with bolted connections. Using this approach, the influence of the low-cycle fatigue (LCF) damage on the behaviour of bolted connections can be studied. Moreover, a Fatigue Damage-Based Hysteretic (FDBH) model is adopted in the proposed approach. The FDBH model is an evolutionary-degrading hysteretic model based on the LCF damage index. This model is an efficient tool in nonlinear response analysis and damage evaluation of steel frame with bolted connections. The model considers the combined effects of damage caused by elasto-plastic behaviour and LCF. The combined damage index forms the basis of this model in that the degradation of stiffness is described as depending on the LCF damage index. Finally, examples of steel portal frames are presented. Nonlinear numerical simulations are performed based on a special finite element code. The dynamic responses of steel frames subjected to seismic excitation are obtained. The paper concludes that the proposed approach can predict the responses of the damaged frames and evaluate the necessity of repair at the damaged connections.

Keywords: Steel frame, bolted connections, random excitation, LCF Fatigue, damage, nonlinear analysis.

INTRODUCTION

Because steel portal frames with bolted connections are expected to undergo some damages during seismic excitation, the damage analysis is essential to assure the safety of civil. It can help to estimate the remaining life or capacity of structures to resist future loads and to reveal the necessity of repair at the damaged locations. However, the damage analysis of a structure requires the introduction of efficient structural models capable of describing the actual behaviour.

Several studies have indicated that bolted connections are vulnerable to the damage accumulation. Plastic hinges usually develop at beam-column connections. The welds and the bolts can be largely affected by LCF which causes progressive and cumulative damage in the stiffness of bolted connections (Tani, 2005).

Different approaches have been developed on the use of a damage index to estimate the structural damage (Tani, 2005; Saranik, 2011). They aim to clarify the different approach methodologies and to detail different proposed formulations. The approaches can be based on the fact that structural stiffness changes as a result of damage. The damage indices proposed in the scientific literature are numerous, and can be defined for each structural element.

Saranik et *al.* (2012) developed a Fatigue Damage-Based Hysteretic (FDBH) model that allowed considering the stiffness degradation produced by the cumulative fatigue damage effects. The FDBH model was a hysteretic model based on LCF damage index. Shaking table tests for a steel portal frame were conducted to verify the validity of the FDBH model and to prove the efficacy of the nonlinear dynamic analysis techniques. The steel portal frame was investigated under horizontal sinusoidal base excitations. However, to analyse a complex structure under seismic excitation, the FDBH model can be used but calculating the LCF damage index is a challenge.

Consequently, this paper presents an approach that was developed to evaluate the performance of steel frames under lateral loads applied by seismic excitation. Two essential phases of analysis must be conducted in this approach to evaluate the accumulation of LCF damage in bolted connections by means of rainflow counting method. FDBH model was used to consider the stiffness degradation produced by the cumulative fatigue damage effects. Furthermore numerical results are carried out to illustrate the accuracy of the approach developed for calculating the LCF damage in steel portal frames with bolted connections.

FDBH MODEL

Saranik *et al.* (2012) proposed a model to include the stiffness degradation of the connection produced by the cumulative phenomenon of LCF. The developed model is named Fatigue Damage-Based Hysteretic FDBH. This degrading hysteretic model is based on a LCF damage index D_n.

In this model, the initial stiffness k_0 is modified with the factor $(1-D_n)$ that takes account of the effect of cumulative fatigue (see Fig. 1).

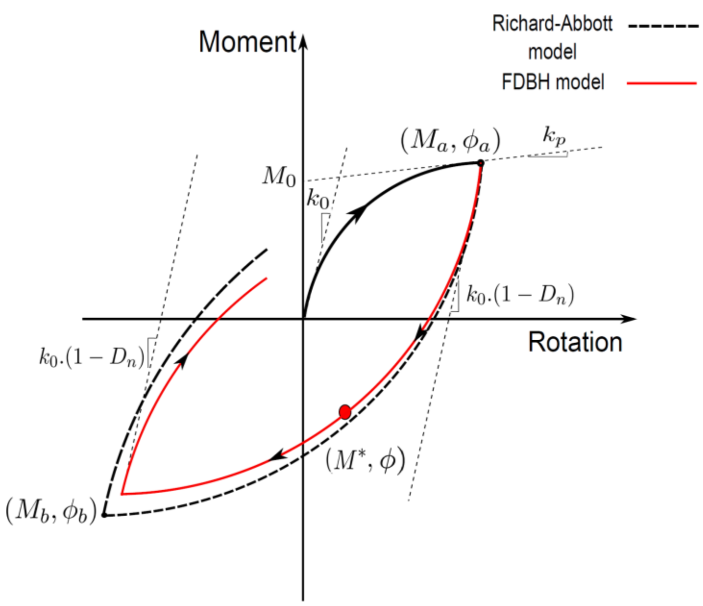

Fig.1 Fatigue Damage-Based Hysteretic model of bolted connection

In this way, the connection loses part of its stiffness in each cycle of excitation applied due to the cumulative phenomenon of LCF. The following equation presents FDBH model for the moment-rotation relationship:

$$M^* = M_a - \frac{(k_0(1-D_n)-k_p)(\phi_a-\phi)}{\left(1+\left|\frac{(k_0(1-D_n)-k_p)(\phi_a-\phi)}{2M_0}\right|^{\gamma}\right)^{\frac{1}{\gamma}}} - k_P(\phi_a-\phi) \tag{1}$$

where M^* is the degraded connection moment, ϕ is the relative rotation between the connecting elements, M_0 is the reference moment, and is the curve shape parameter. D_n is the fatigue damage index and k_p is the final plastic stiffness. (M_a, ϕ_a) is the load reversal point and (M_b, ϕ_b) is the next load reversal point as shown in Fig. 1. Saranik *et al.* (2012) also proposed a value of the plastic stiffness $k_p = 0$ which can simplify the model.

The tangent stiffness of the connection element can be written as:

$$k^* = \frac{(k_0(1-D_n)-k_p)}{\left(1+\left|\frac{(k_0(1-D_n)-k_p)(\phi_a-\phi)}{2M_0}\right|^{\gamma}\right)^{\frac{\gamma+1}{\gamma}}} + k_P \tag{2}$$

where k^* is the degraded secant stiffness.

In this way, the secant stiffness in Eq. (2) can be modified and it is possible to combine the two indices by the equation:

$$D_p = 1 - \frac{k^*}{k_0} \tag{3}$$

where D_p is the plastic damage index. It can be observed that D_p depends on the tangent stiffness k^* of the connection and the LCF damage index D_n.

The FDBH model of Saranik *et al.* (2012) uses recent concepts in the structural damage evaluation and it can allow taking account of the stiffness degradation produced by the cumulative fatigue damage effects. Thereby, the FDBH model is an efficient model to simulate inelastic response of structure under dynamic loading by combined damage indices.

To evaluate fatigue damage in structural components under arbitrary loading histories, Miner's rule is commonly employed (Tani, 2005; Miner, 1945). Some global parameter such as plastic rotation can be used rather than strains or stress for applying Miner's rule. In the case of connection subjected to many cycles of rotation, Miner's rule is expressed by the following equation:

$$D_n = \sum_i \frac{n_i}{Nf_i} \tag{4}$$

where n_i is the number of applied cycles for a given rotation level i and Nf_i is the number of cycles to failure for a rotation level i.

Moreover, to calculate the number of cycles to failure Nf, an analogous model based on the plastic connection rotation must be utilised therein. The information provided by the Rotation-Number of cycles curve is mainly applied by engineers for the prediction of the lifetime and resistance of structures under repeated loading. A useful method of describing the LCF life is expressed by Mander *et al.* (1994) for a bolted connection. Thus using the well-known Manson-Coffin relationship (Gillis, 1966), the plastic rotation may be related to the number of cycles to failure Nf by the following equation:

$$Nf = c(\Delta\phi_p)^{-b} \tag{5}$$

where ϕ_p is the plastic rotation of the connection. c and b are the parameters of fatigue which depend on both the typology and the mechanical properties of the considered steel element. From experimental fatigue results performed by Saranik *et al.* (2012), the fatigue parameters of Manson-Coffin are ($c=22\times10^{-5}$) and ($b=3$). These parameters are used to analyse steel portal frames in this study. Manson-Coffin relation describes linearly this function between the applied rotation and the number of cycles to rupture on a double-logarithmic scale.

FINITE ELEMENT ANALYSIS

If a structure is properly modelled using Finite Element FE, structural damage manifests itself mathematically in the stiffness and mass matrices, as well as physically in its dynamic properties such as natural frequencies and mode shapes (Saranik, 2012; Saranik, 2011). In this study, the damage in the structure could be identified as a change in FE stiffness matrices of the different beam elements of the structure. The FE model of the structure was a two-dimensional model developed by the Structural Dynamics Toolbox (SDT) with MATLAB 7.6 (R2008a) (Balmes, 2009).

The equation of motion for a damped structure with N degrees-of-freedom (dof) is given as follows:

$$\mathbf{M}\ddot{\mathbf{q}} + \overline{\mathbf{C}}\dot{\mathbf{q}} + \overline{\mathbf{K}}\mathbf{q} = \mathbf{F}(t) \tag{6}$$

where $\mathbf{M}$, $\overline{\mathbf{C}}$ and $\overline{\mathbf{K}}$ are respectively the mass, nonlinear damping and nonlinear stiffness matrix of the structure. $\mathbf{F}(t)$ is the applied forces vector and $\mathbf{q}$ is the relative response of system in normal coordinate. The stiffness matrix is nonlinear due to the nonlinearity of the beam-column connections and depends on the response of system and the nonlinear normal modes.

For a structure excited at the base, the right-hand side of Eq. (6) can be interpreted as effective dynamic forces according to Chopra *et al.* (2002):

$$\mathbf{F}(t) = -\mathbf{M}\iota\ddot{\mathbf{q}}_{\mathbf{r}} \tag{7}$$

where ι and $\ddot{\mathbf{q}}_{\mathbf{r}}$ are respectively the vector of influence coefficients and the horizontal random base excitation. Rayleigh damping can be used to represent damping in the structure. It can be written as:

$$\overline{\mathbf{C}} = \alpha\mathbf{M} + \beta\overline{\mathbf{K}} \tag{8}$$

where α and β are the proportional damping factors.

The elements in the steel frame can be modeled as Euler-Bernoulli beams and each element beam or column is discretized into four finite elements. The matrix can be assembled by the stiffness matrices of each beam and column element in the system with the following equation:

$$\overline{\mathbf{K}} = \sum_{e=1}^{n_e} \overline{\mathbf{k}}_e \tag{9}$$

where n_e is the total number of elements in the system and members are generically identified by index e.

The nonlinear matrix for an element can be calculated using the correction matrix with the following equation (Saranik, 2012):

$$\overline{\mathbf{k}}_e = \mathbf{k}_e \mathbf{C}_{re} \tag{10}$$

where $\mathbf{k}_e$ is the standard elastic stiffness matrix for the element. The correction matrix $\mathbf{C}_{re}$ is given as follows:

$$\mathbf{C}_{r_e} = \sum_q \sum_s c_{qs_e} : c_{qs_e} = f\left(D_{p_{e,l}},\ D_{p_{e,r}},\ L\right) \tag{11}$$

where $D_{p_{e,l}}$ and $D_{p_{e,r}}$ are the plastic damage indices of the connections (left l and right r, respectively) for the considered element. L is the length of this element.

According to Saranik *et al.* (2012), eigenvalues and eigenvectors for a nonlinear system cannot be obtained by solving the standard eigenvalue problem. As the solution of a nonlinear system relies heavily on the amplitude of excitation, the frequencies and normal modes depend on the nonlinear modal amplitude. The introduction of the notion of nonlinear modes permits an extension of the method of linear modal synthesis to nonlinear cases in order to obtain the dynamical response of nonlinear multi-degree-of freedom systems.

The nonlinear normal modes and nonlinear frequencies can be calculated by an iterative procedure (Saranik, 2012; Setio, 1992). In this paper, a procedure which is based on the method of equivalent linearisation was adopted. Considering the FE methods, the nonlinear modal problem can be written as following:

$$\left[\ \overline{\mathbf{K}}(\eta_{p_i}, \overline{\varphi}_{p_i}(\eta_{p_i})) - \overline{\omega}^2_{p_i}(\eta_{p_i})\mathbf{M}\ \right] \overline{\varphi}_{p_i}(\eta_{p_i}) = 0 \tag{12}$$

where η_{p_i}, $\overline{\omega}^2_{p_i}(\eta_{p_i})$ and $\overline{\varphi}_{p_i}(\eta_{p_i})$ are respectively the structural response of the i^{th} mode in modal coordinate, the nonlinear frequency and the nonlinear normal mode i.

For each time step of calculation, the stiffness and damping matrices of the system can be obtained that may transform the nonlinear system into an equivalent linear system. The frequencies and nonlinear normal modes can then be calculated using a standard solution of the eigenvalue problem given by Eq. (12). A set of N nonlinear modes and frequencies can be obtained according to their modal amplitudes.

For this purpose, the response of nonlinear system in normal coordinate can be calculated efficiently by superposition of modal response as follows:

$$\mathbf{q}(t) = \overline{\varphi}_p\ \boldsymbol{\eta}_p(t) \tag{13}$$

To solve the equation of motion given by Eq. (6), iterative procedures can be used.

DEVELOPED APPROACH FOR LCF ANALYSIS

The analysis of LCF damage using indicators of damage for each bolted connection in a complex system is a delicate and difficult problem, especially when the system is subjected to a random base excitation (Agerskov, 2000). Under random base excitation, two problems can be confronted in the analysis of damage of a bolted connection.

The first one is that, the response of the connection is random and it is necessary to locate and identify each complete or half cycle of rotation. A counting of cycles must be made to constitute a histogram of the cycles of the random rotation and under random base excitation, the distribution of rotation cycles and levels of amplitude versus time are difficult to obtain.

The second problem is that the signal measured, in general a random response, is not only made up of a peak alone between two passages by zero, but also several peaks appear, which makes difficult the determination of the number of cycles absorbed by the connection. The presence of such these cycles leads to a noise in the rotation-time response, and this complicates the counting of cycles. This noise should be ignored because they do not consider as real cycles.

Therefore, an adequate algorithm must be developed to analyse the LCF damage in a steel frame structure subjected to random excitation. An approach based on a simplified algorithm is proposed in this study. The algorithm, presented in Fig. 2, aims to evaluate the performance of steel frames with bolted connections under random base excitation. Using this algorithm, the influence of the LCF damage on the behaviour of bolted connection can be studied.

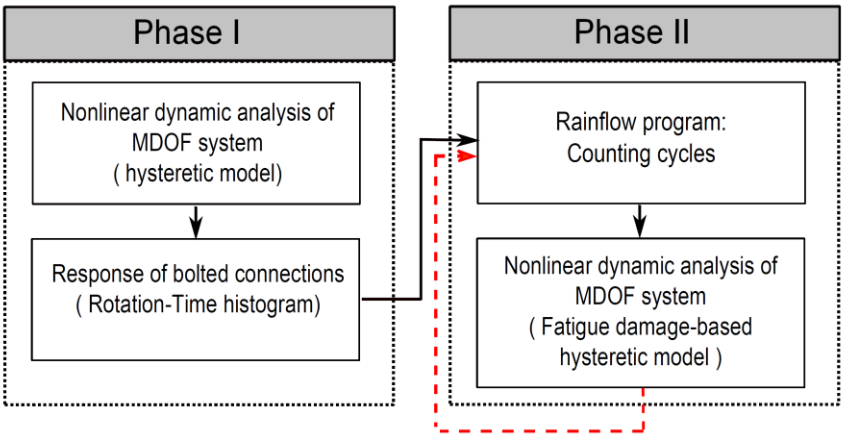

Fig.2 Flowchart of the proposed algorithm

The objective of the first one is to prepare a nonlinear modal analysis of the structure using the hysteretic model. This phase is important to prepare the necessary data for the second phase. In this phase, the rotation-time histograms will be obtained. These histograms are necessary to prepare an analysis of LCF damage.

In the second phase, a cycle counting program, *rainflow program*, can be used through the Matlab toolbox offered by A. Nieslony (2007). This program analyses the histograms to find the number of cycles counted, the corresponding rotational levels and the corresponding times. A Fatigue Damage-Based Hysteretic FDBH model will be used, following in the second phase, to prepare a nonlinear modal analysis of the structure and to combine the damage caused by elasto-plastic behaviour and LCF.

NUMERICAL RESULTS

A numerical example for three-story two-bay plane steel frame with bolted connections is presented in this section in order to illustrate the proposed approach and demonstrate its advantages. The nominal values of yield strength f_y and the ultimate values of tensile strength f_u of the steel profile sections used in these examples are respectively 280 MPa and 480 MPa. The steel members of the frame have a 210 GPa elasticity modulus.

The frame shown in Fig. 3 is employed to determine if the proposed algorithm can be used to evaluate the accumulation of LCF damage in complex structure with bolted connections and to detect the damage in dynamic properties such as natural frequencies and mode shapes.

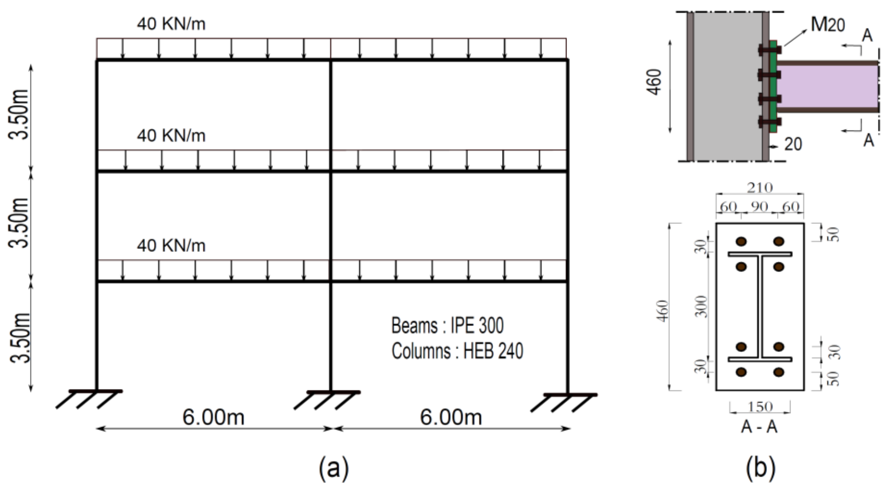

Fig.3 Three-story steel portal frame: (a) details of the portal frame (in m); (b) details of the bolted connection (in mm)

This investigation examines the behaviour of the frame with bolted connections under random base excitation. The portal frame model has a width of 12 m and a height of 10.5 m. The beams of the portal frame are a straight beam with an I cross section. The beam to column connections are bolted connections as shown in Fig. 3(b).

The beam and column sections are chosen from Standard European Steel profiles IPE 300 and HEB 240, respectively. Eight standard bolts M20 are employed for each connection of the beam. The general layout of the end plate is shown in Fig. 3(b), with the thickness (20 mm) and dimensions (460 mm × 210 mm) of the plate detailed. The initial stiffness and the ultimate moment calculated according to Eurocode 3 are k_0 = 3.475 × 105 KN.m/rad and M_u = 134.4 MPa, respectively (CEN, 2005). The yielding moment of the connection can be evaluated as M_y=2/3M_u=89.6 MPa.

Two failure criteria are considered in numerical simulations. The first one is the connection rotation and it must not exceed the maximum value $\phi_{\max}$, which is equal in this study to $\phi_{\max}$=0.045 rad (Yun, 2008). The second is the index D_n and it must not exceed the value of (1). If both criteria are not met, the connection will be considered as a hinge.

The portal frame is subjected to gravity loads of the dead load plus a 40 KN/m live load, according to Fig. 3(a) and it was excited by an earthquake (normalized El-Centro) with a peak ground acceleration of $|\ddot{q}_r|_{\mathbf{max}}$ = 2 m/sec^2.

Moreover, the natural frequencies of the frame were determined using the numerical simulation based on FE model developed by Structural Dynamics Toolbox (SDT) with MATLAB. The first natural frequency was estimated to be 1.58 Hz. The horizontal displacements, connection rotations and the moment-rotation responses of bolted connections were obtained by the application of the proposed algorithm.

Figs. 4 and 5 illustrate the numerical story displacements of the frame and the rotation responses of bolted connections ϕ_1, ϕ_2 and ϕ_3.

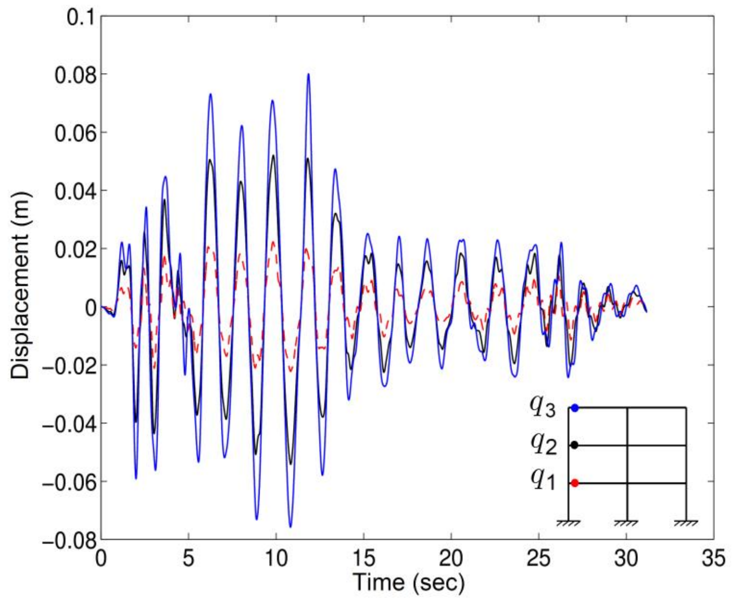

Fig.4 Displacement story responses of the frame under excitation with $|\ddot{q}_r|_{\mathbf{max}}$ = 2 m/sec^2

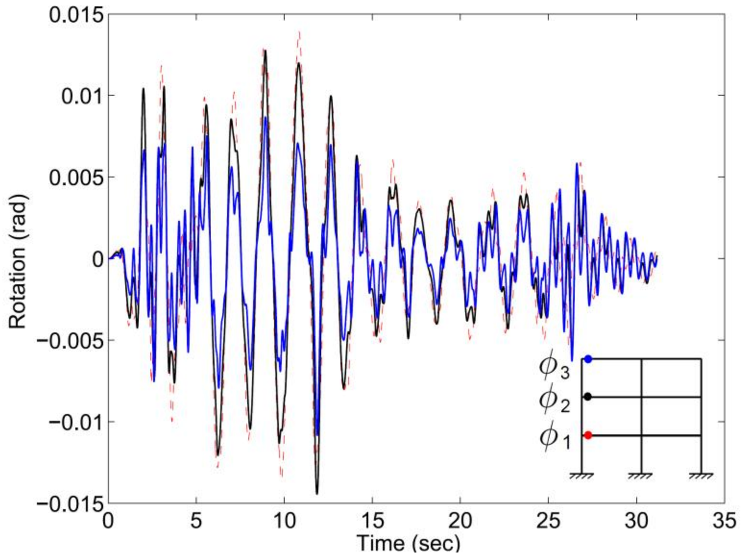

Fig.5 Rotation responses of connections in frame under excitation with $|\ddot{q}_r|_{\mathbf{max}}$ = 2 m/sec^2

The numerical values of LCF damage indices are displayed in Fig. 6. They present the damage indices for connections 1 and 3. Accordingly, the connection 1 is totally damaged at t = 1.7 sec after the damage induced by plasticity and the development of a plastic hinge. The numerical values of the plastic damage indices are equal to 100% for this connection at the first story. The value of LCF damage index D_{n1} is equal to 0.7% at the same time. However, the numerical values of the plastic damage index for connection 3 reach a value of 100% at t = 7.3 sec. But, the value of LCF damage index D_{n3} for connection 3 reached a value of 11.9%. These results mean that the effects of damage by plasticity are more dominant in this example than the LCF damage. The connections 1 and 3 are totally damaged after 1.7 sec and 7.3 sec, respectively.

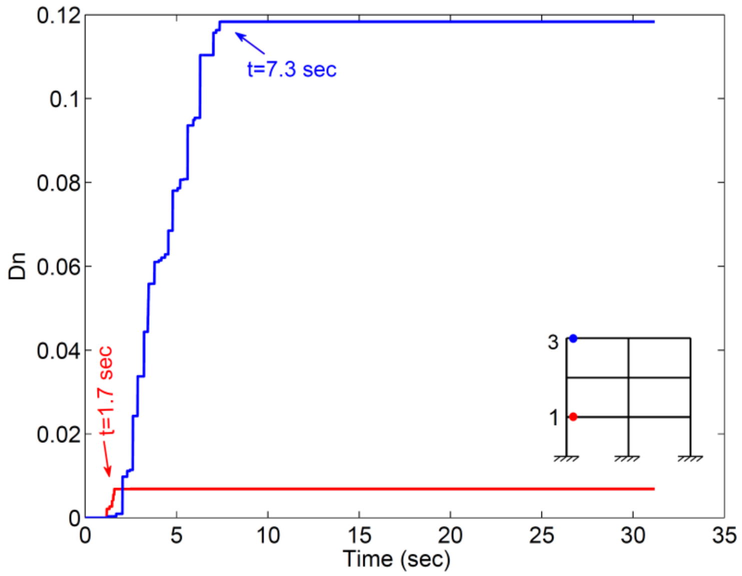

Fig.6 LCF damage index of connections 1 and 3 in the frame under excitation with $|\ddot{q}_r|_{\mathbf{max}}$ = 2 m/sec^2

Numerically, the loss of the first natural frequency is clearly observed (see Fig. 7). The numerical results reveal that the natural frequency f_{n1} decreases from initial value 1.58 Hz to a final value 1.15 Hz during the excitation. The results of this example confirmed the presence of changes in natural frequencies, because of the damage in bolted connections of the frame. The diminution of natural frequency values with increasing damage was a direct result of the damage in some bolted connections and the failure in others.

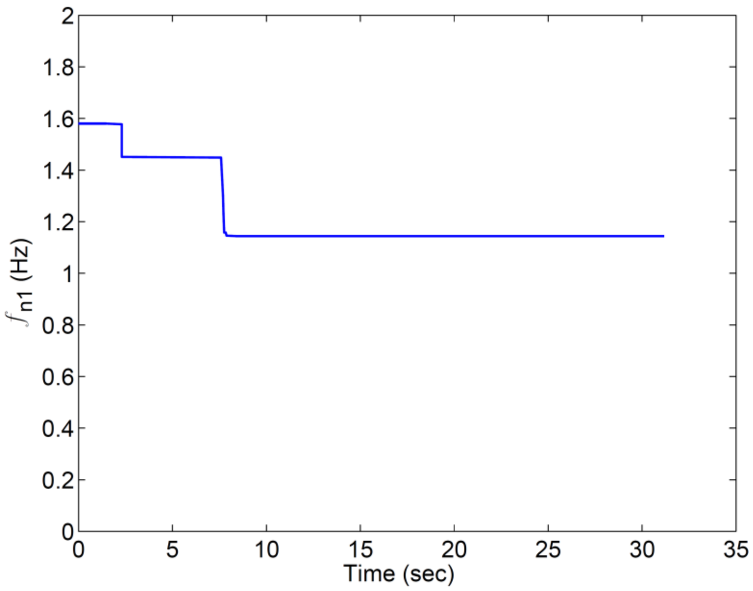

Fig.7 First natural frequency of the frame in the frame under excitation with $|\ddot{q}_r|_{\mathbf{max}}$ = 2 m/sec^2

After increasing the peak acceleration of the random excitation to $|\ddot{q}_r|_{\mathbf{max}}$ = 3.6 m/sec^2, the portal frame was recalculated according the developed algorithm. As the previous analysis, the damage indices for connections 1 and 3 are presented in Fig. 8.

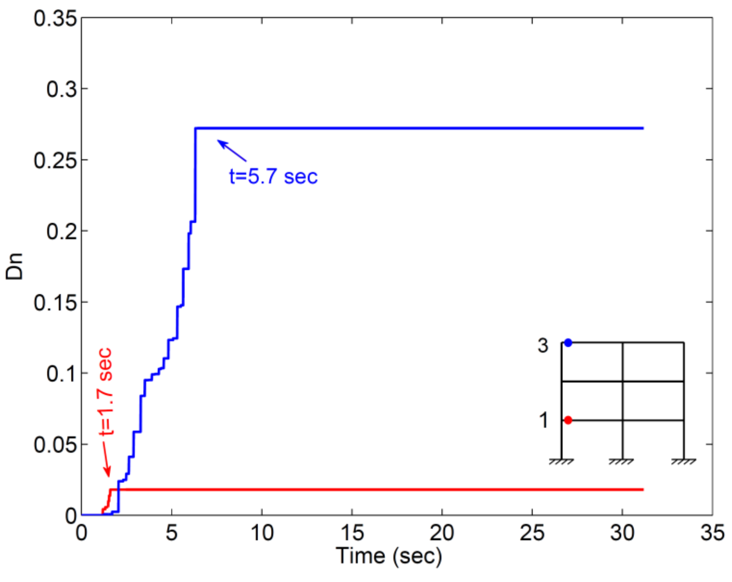

Fig.8 LCF damage index of the connections 1 and 3 in the frame under excitation with $|\ddot{q}_r|_{\mathbf{max}}$ = 3.6 m/sec^2

The connection 1 is totally damaged at t = 1.7 sec because of the damage induced by plasticity and the development of a plastic hinge. The numerical value of the plastic damage index is equal to 100% for this connection at the first story. The value of LCF damage index D_{n1} is equal to 1.9 % at the same time. However, the numerical values of the plastic damage index for connection 3 reach a value of 100% at t = 5.7 sec. But, the value of LCF damage index D_{n3} for connection 3 reaches a value of 27%.

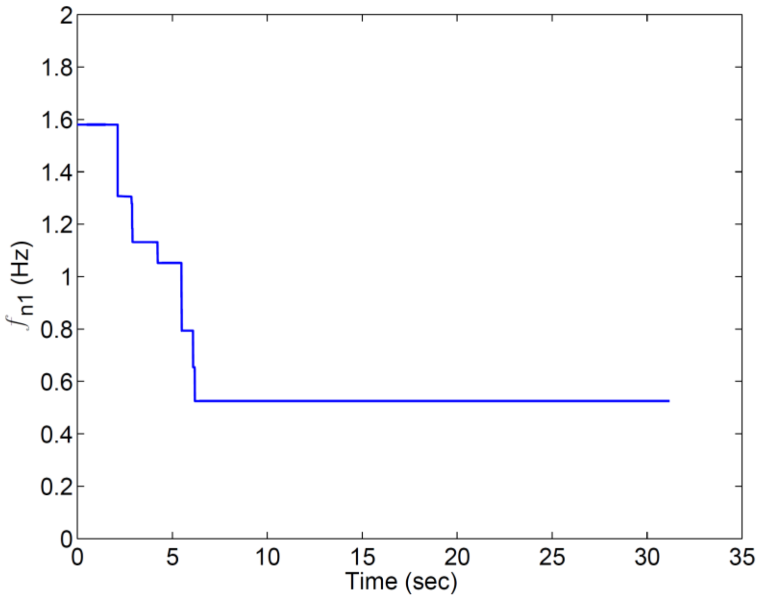

Fig.9 First natural frequency of the frame in the frame under excitation with $|\ddot{q}_r|_{\mathbf{max}}$ = 3.6 m/sec^2

These results mean that the effects of damage by plasticity were more dominant in this example than the LCF damage. But, the LCF damage in connections has significant impact in their behaviours and dynamic properties. The numerical results demonstrate the loss of the first natural frequency (see Fig. 9). The results reveal that the natural frequency f_{n1} decreases from initial value 1.58 Hz to a final value 0.53 Hz during the excitation. A drop in frequency due to the development of plastic hinges during the applied excitation is observed numerically.

However, the results of the two analyses presented in this example confirm that the damage in bolted connections depends directly on the acceleration amplitude of the random base excitation applied to the steel portal frame. Also, the results indicate the possibilities for predicting the damage in connections under random excitation using the developed algorithm. The algorithm can help to estimate the remaining life or capacity of complex structures to resist future random excitation and to reveal the necessity of repair at the damaged connections.

CONCLUSION

In this paper, an approach for nonlinear analysis of steel portal frames subjected to seismic excitations is presented. The approach aims to evaluate the performance of steel portal frames with bolted connections and to study the influence of the LCF damage on the behaviour of these structures. The approach uses an algorithm which consists of two phases of analysis.

An example is performed to illustrate the proposed numerical approach and the results. A comparison between the response results is also carried out. The proposed approach appears to be a good tool to consider the influence of LCF phenomena and the plastic damage phenomena on the behaviour of the bolted connection. The approach can estimate the remaining life of steel portal frames after applying a seismic excitation.

However, the approach can evaluate the capacity of steel portal frames to resist future seismic excitation and to reveal the necessity of repair at the damaged connections. Results of numerical examples demonstrate that the damage in steel portal frames depends essentially on the duration, the frequency and the acceleration amplitude of the seismic excitation.

REFERENCES

Tani I, Lenoir D, and Jézéquel L. Effect of junction stiffness degradation due to fatigue damage of metallic structures. Engineering Structures, 27(11):1677 – 1688, 2005.

Saranik M, Lenoir D, and Jézéquel L. Effects of low cycle fatigue damage in the end plate connection on steel frame seismic demands. 8th International Conference on Structural Dynamics (EURODYN 2011), Leuven, Belgium, July 4-6, 2011.

Saranik M, Lenoir D, and Jézéquel L. Shaking table test and numerical damage behaviour analysis of a steel portal frame with bolted connections. Journal Computers and Structures, Volumes 112–113, December 2012, Pages 327-341.

Miner M.A. Cumulative damage in fatigue. Journal of Applied Mechanics, 12(Trans. ASME Vol. 67):A159 – A164, 1945.

Saranik M, Lenoir D, and Jézéquel L. Effects of low cycle fatigue damage in the end plate connection on steel frame seismic demands. 8th International Conference on Structural Dynamics (EURODYN 2011), Leuven, Belgium, July 4-6, 2011.

Mander John B, Chen Stuart S, and Pekcan Gokhan. Low-cycle fatigue behavior of semi-rigid top-and-seat angle connections. AISC Engineering Journal, 31(3):111 – 124, 1994.

Gillis P.P. Manson-coffin fatigue. Acta Metallurgica, 14(12):1673 – 1676, 1966.

Saranik M, Lenoir D, and Jézéquel L. Nonlinear seismic analysis and fatigue-accumulated damage of steel frames with end-plate bolted connections. 3rd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2011), Corfu, Greece, May 25-28, 2011. http://www.scopus.com.

Balmes E, Bianchi J, and Leclére J. Structural dynamics toolbox 6.2 (for use with matlab), sdtools. Paris, France, www.sdtools.com, Sep 2009.

Chopra A.K and Goel R.K. A modal pushover analysis procedure for estimating seismic demands for buildings. Earthquake Engineering and Structural Dynamics, 31(3):561 – 582, 2002.

Setio S, Setio H.D, and Jézéquel L. A method of non-linear modal identification from frequency response tests. Journal of Sound and Vibration, 158(3):497 – 515, 1992.

Agerskov Henning. Fatigue in steel structures under random loading. Journal of Constructional Steel Research, 53(3):283 – 305, 2000.

Nieslony A and Macha E. Spectral method in multiaxial random fatigue. Lecture Notes in Applied and Computational Mechanics, Vol. 33:pp. 8, 2007.

CEN European Committee for Standardisation. Design of steel structures. Part 1-1: General rules and rules for buildings, EN 1993-1-1, Brussels (Belgium), 2005.

Yun Gun Jin, Ghaboussi Jamshid, and Elnashai Amr S. A design-variablebased inelastic hysteretic model for beam-column connections. Earthquake Engineering and Structural Dynamics, 37(4):535 – 555, 2008.